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**Vasadi et al.**

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(54) **POWER MANAGEMENT UNIT SYSTEMS AND METHODS**

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(51) **Int. Cl.**

| | |
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| ***H02M 3/158*** | (2006.01) |
| *H02M 1/00* | (2007.01) |

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(58) **Field of Classification Search**

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See application file for complete search history.

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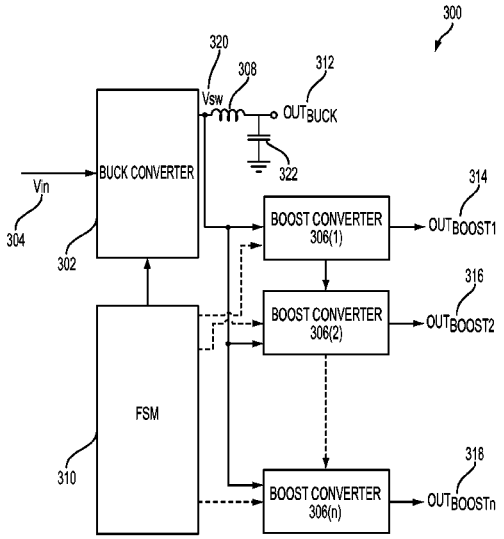
(57) **ABSTRACT**

Systems and methods provide for a power management unit and its operation. The power management unit includes: a step-down power converter configured to receive a first voltage and output a second voltage, wherein the second voltage is less than the first voltage and at least one step-up power converter configured to receive the second voltage and output a third voltage, wherein the third voltage is greater than the second voltage. It also includes an inductive element connected to the step-down power converter and the at least one step-up power converter and configured to store energy and selectively release the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter; and a finite state machine configured to control the time sharing of the inductive element.

**25 Claims, 12 Drawing Sheets**



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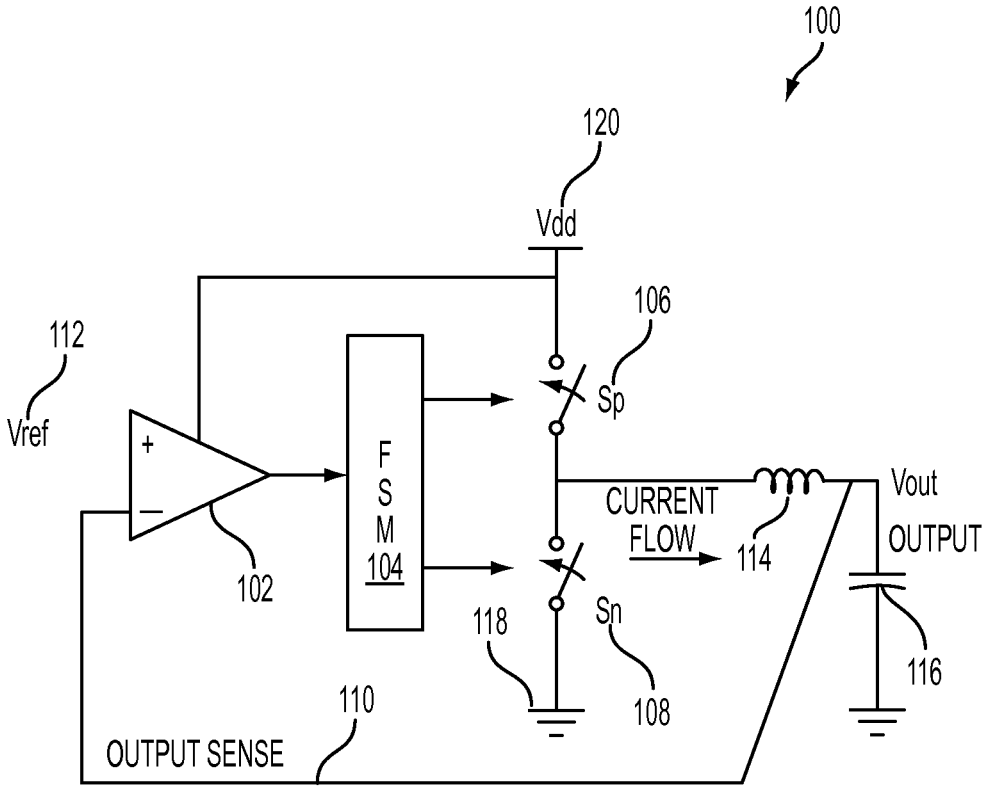



FIG. 1
BACKGROUND ART

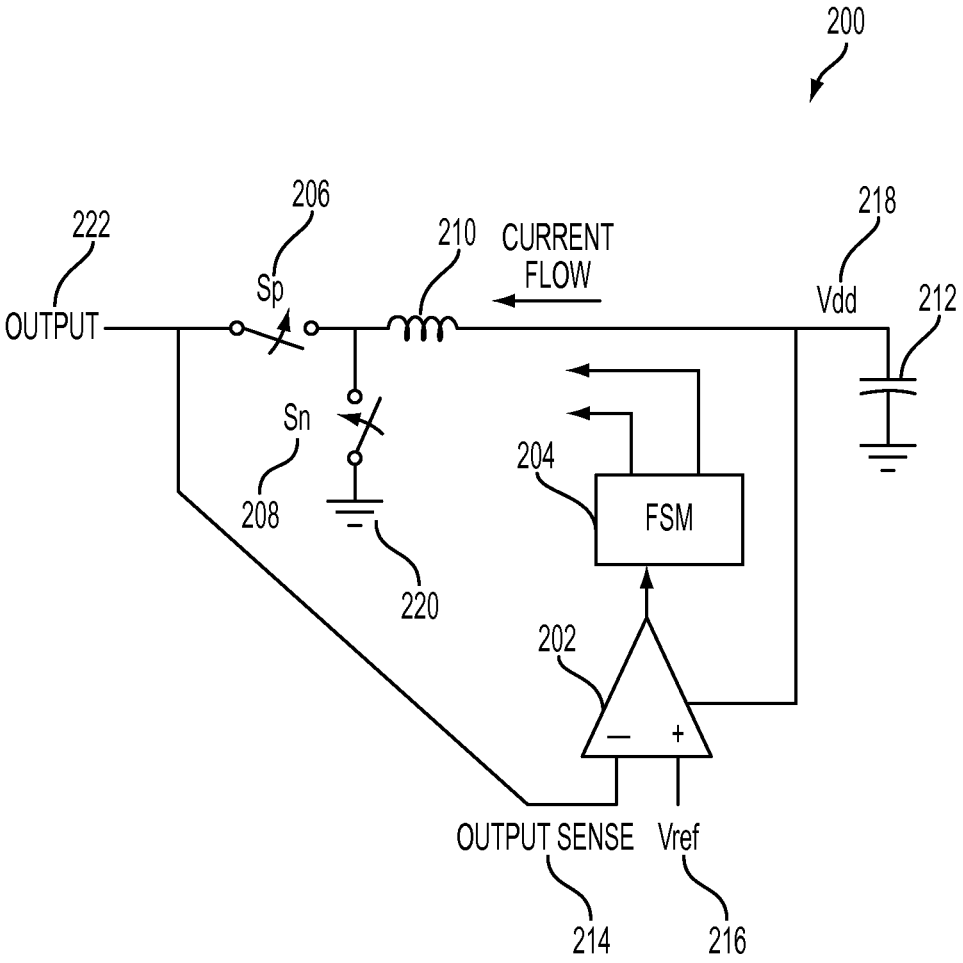
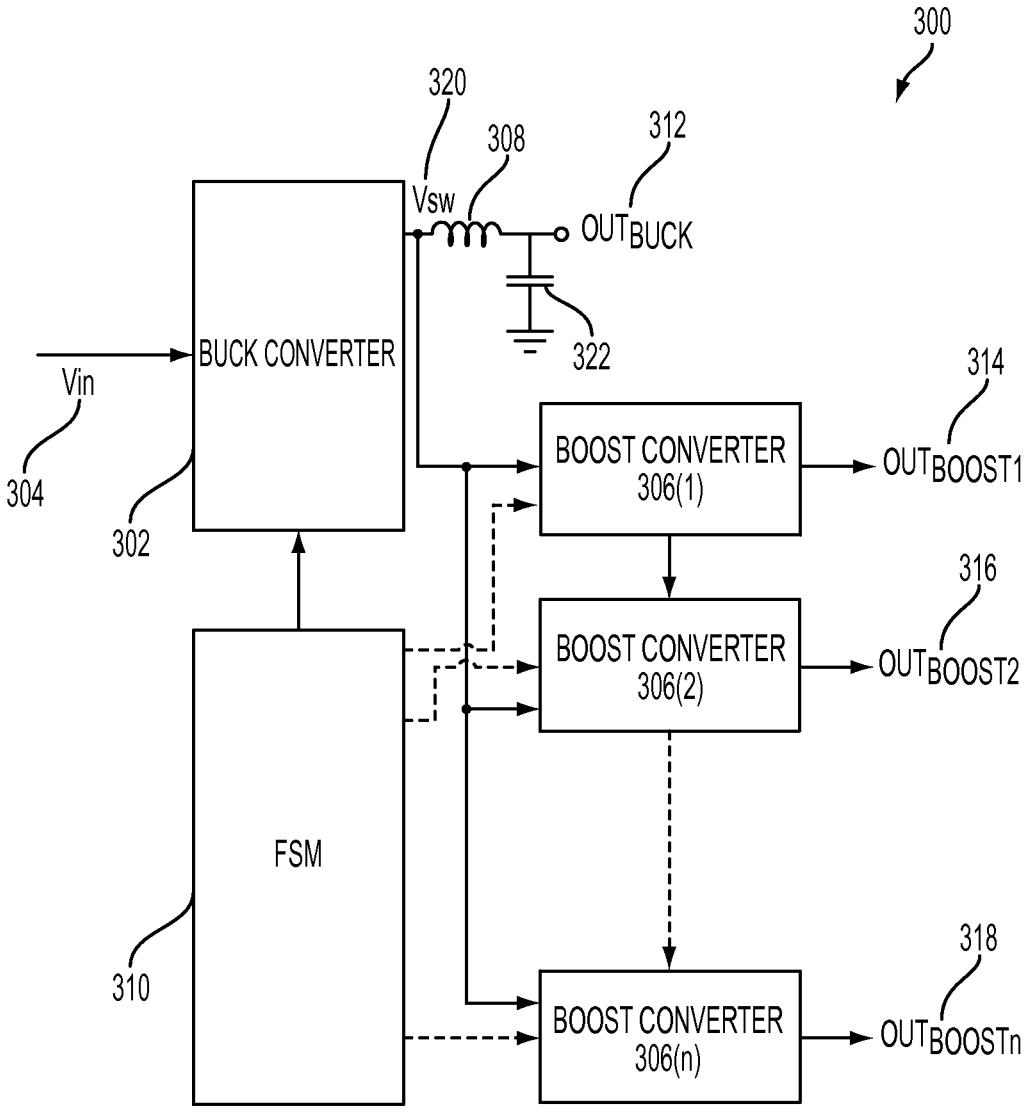



FIG. 2
BACKGROUND ART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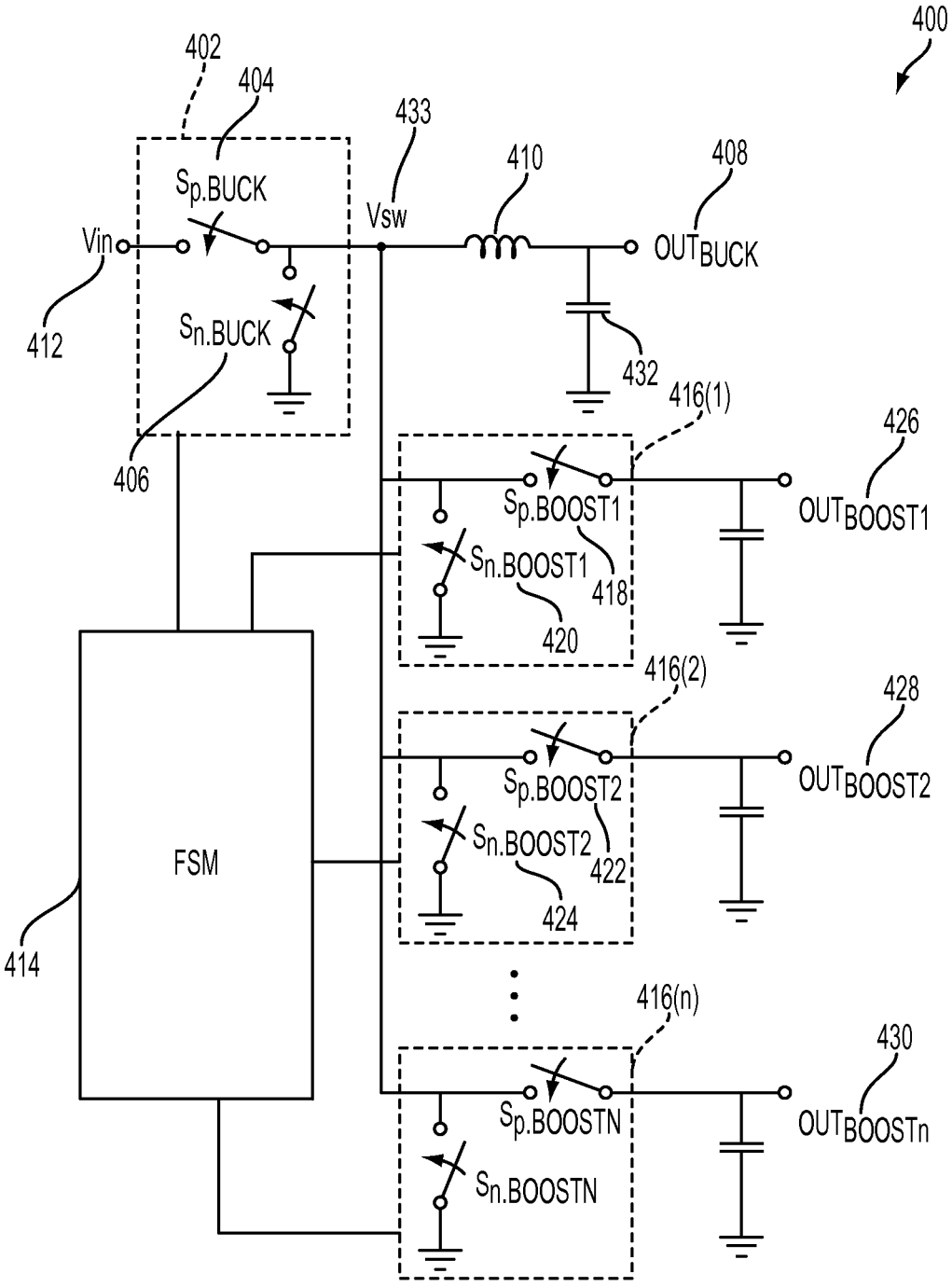
320
308
312
Vsw
OUTBUCK
322
BUCK CONVERTER
Vin
304
302
314
BOOST CONVERTER
306(1)
OUTBOOST1
316
BOOST CONVERTER
306(2)
OUTBOOST2
FSM
310
318
BOOST CONVERTER
306(n)
OUTBOOSTn

FIG. 3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404
433
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408
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Vin
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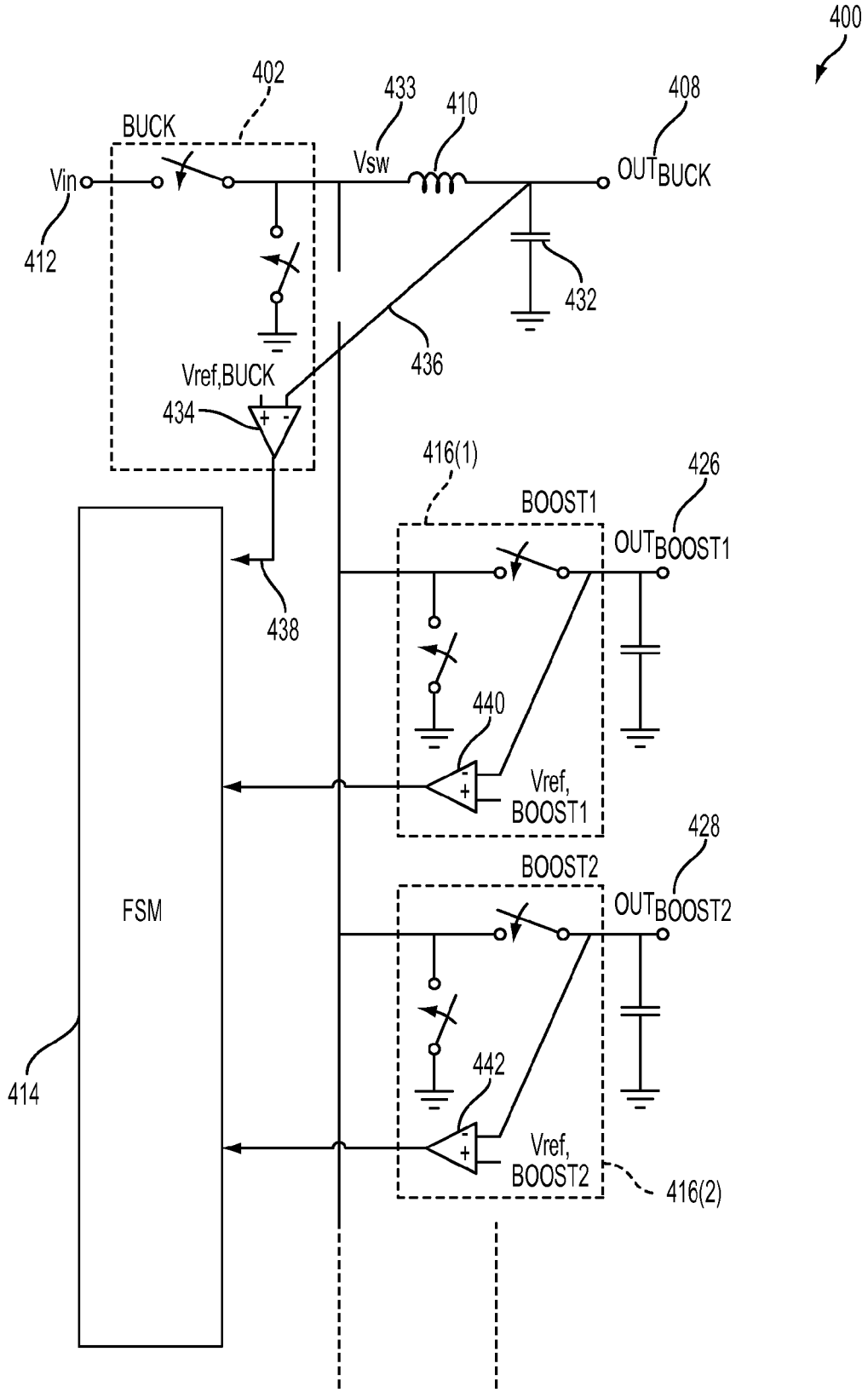
Sn.BUCK
432
416(1)
426
406
Sp.BOOST1
OUTBOOST1
Sn.BOOST1
418
420
416(2)
428
Sp.BOOST2
OUTBOOST2
FSM
Sn.BOOST2
422
424
414
416(n)
430
Sp.BOOSTN
OUTBOOSTn
Sn.BOOSTN

FIG. 4A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426
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BOOST1
428
BOOST2
OUTBOOST2
FSM
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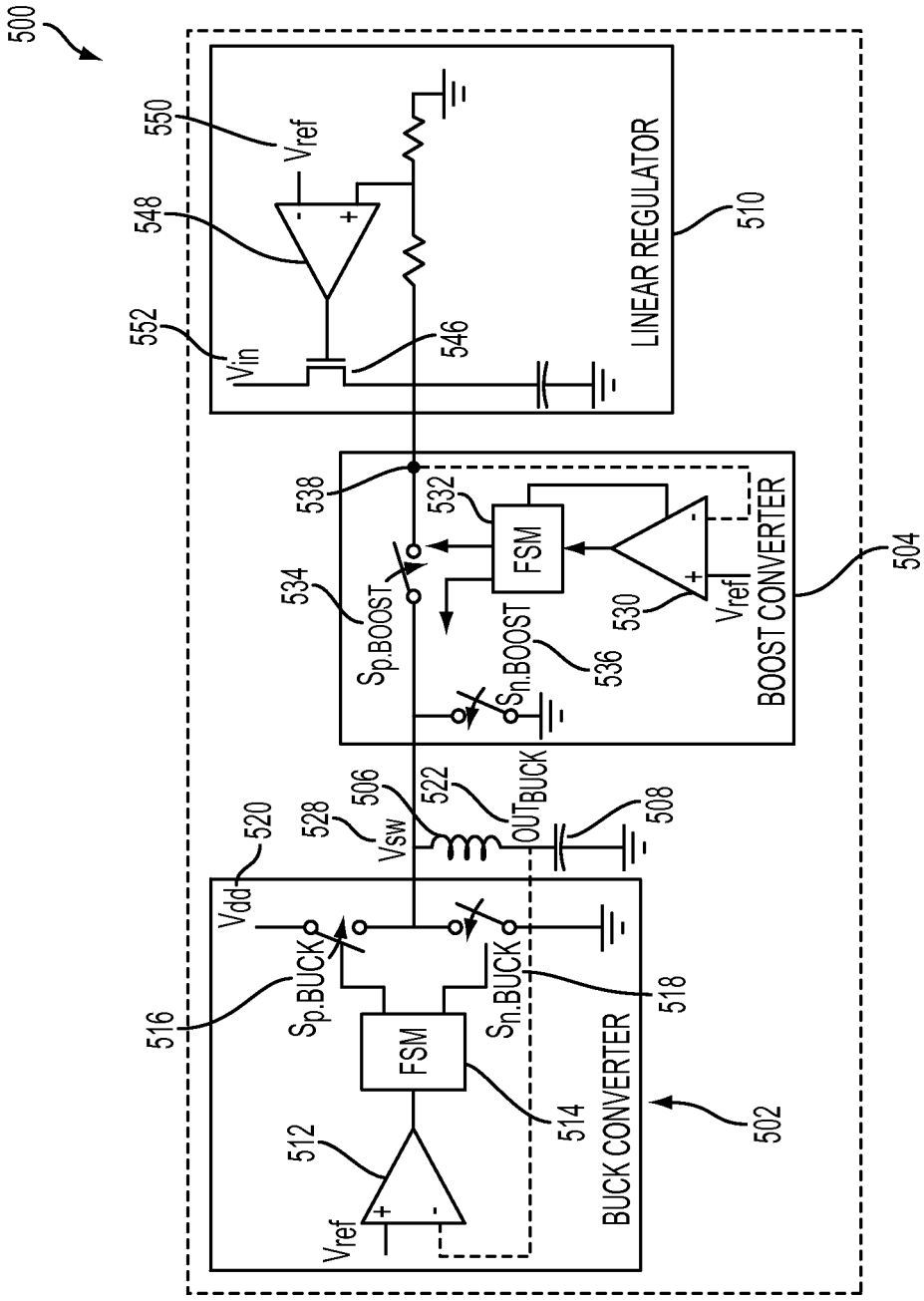
442
Vref,
BOOST2
416(2)

FIG. 4B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Vref
548
552
Vin
546
LINEAR REGULATOR
510
538
532
FSM
534
Sp.BOOST
530
Vref
Sn.BOOST
536
BOOST CONVERTER
504
506
522
528
Vsw
OUTBUCK
508
520
Vdd
Sp.BUCK
516
Sn.BUCK
518
FSM
514
512
Vref
BUCK CONVERTER
502

FIG. 5A

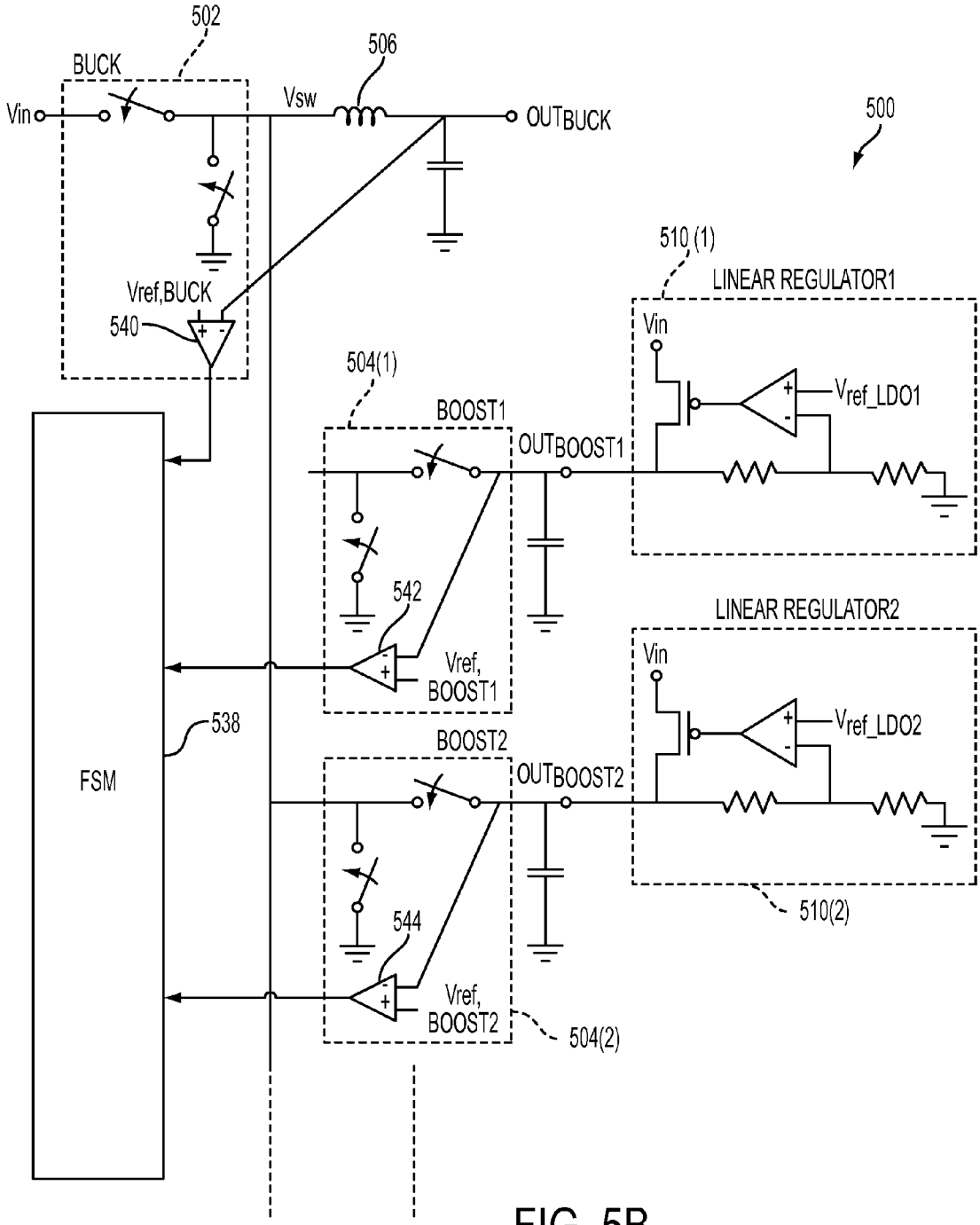
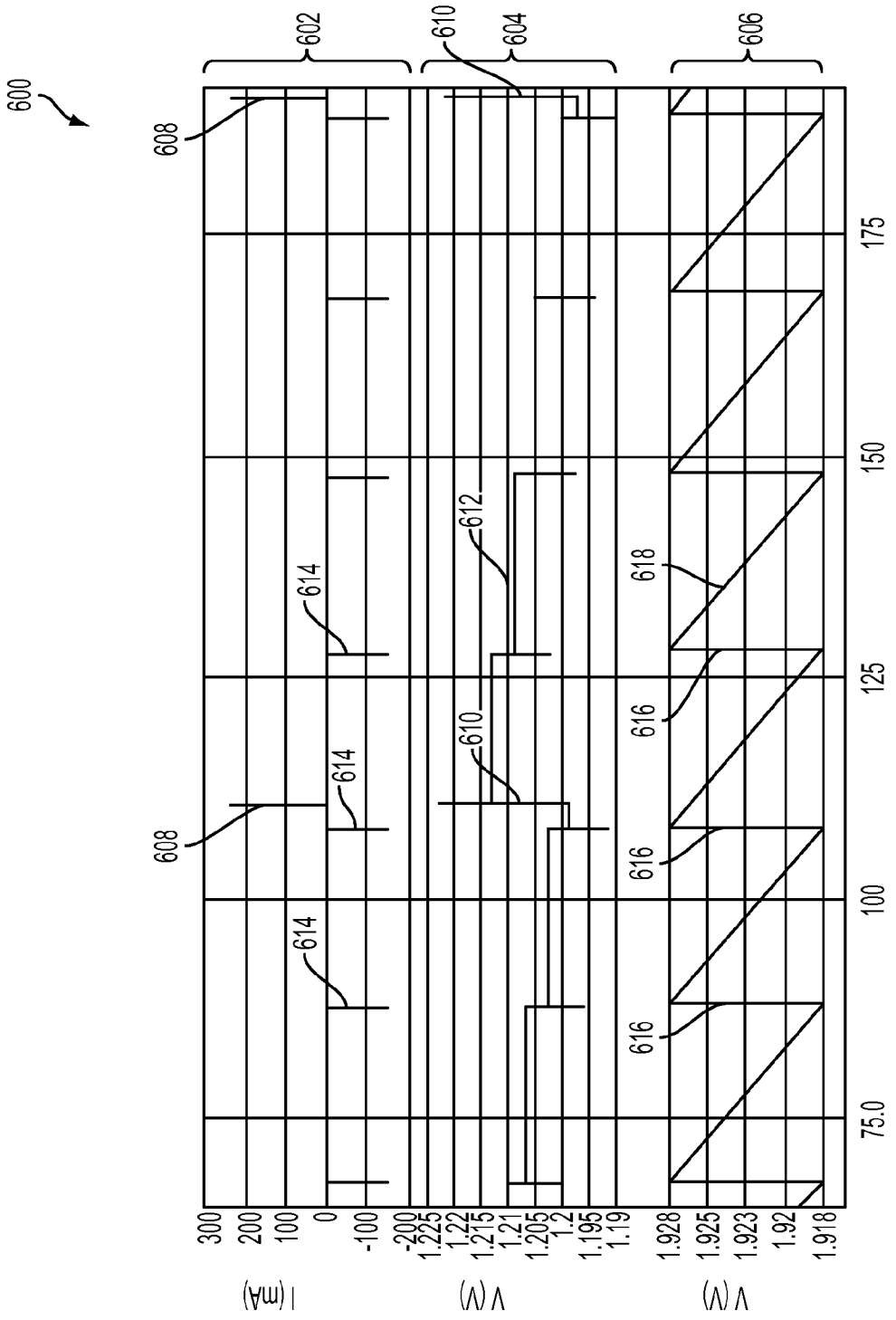

502
BUCK
506
Vin
Vsw
OUTBUCK
500
510(1)
LINEAR REGULATOR1
Vref,BUCK
540
Vin
504(1)
Vref_LDO1
BOOST1
OUTBOOST1
542
LINEAR REGULATOR2
Vin
Vref,
BOOST1
538
Vref_LDO2
BOOST2
OUTBOOST2
FSM
544
510(2)
Vref,
BOOST2
504(2)

FIG. 5B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602
604
606
608
610
612
614
616
618
I (mA)
V (V)
V (V)
TIME (US)
300
200
100
0
-100
-200
1.225
1.22
1.215
1.21
1.205
1.2
1.195
1.19
1.928
1.925
1.923
1.92
1.918
75.0
100
125
150
175

FIG. 6

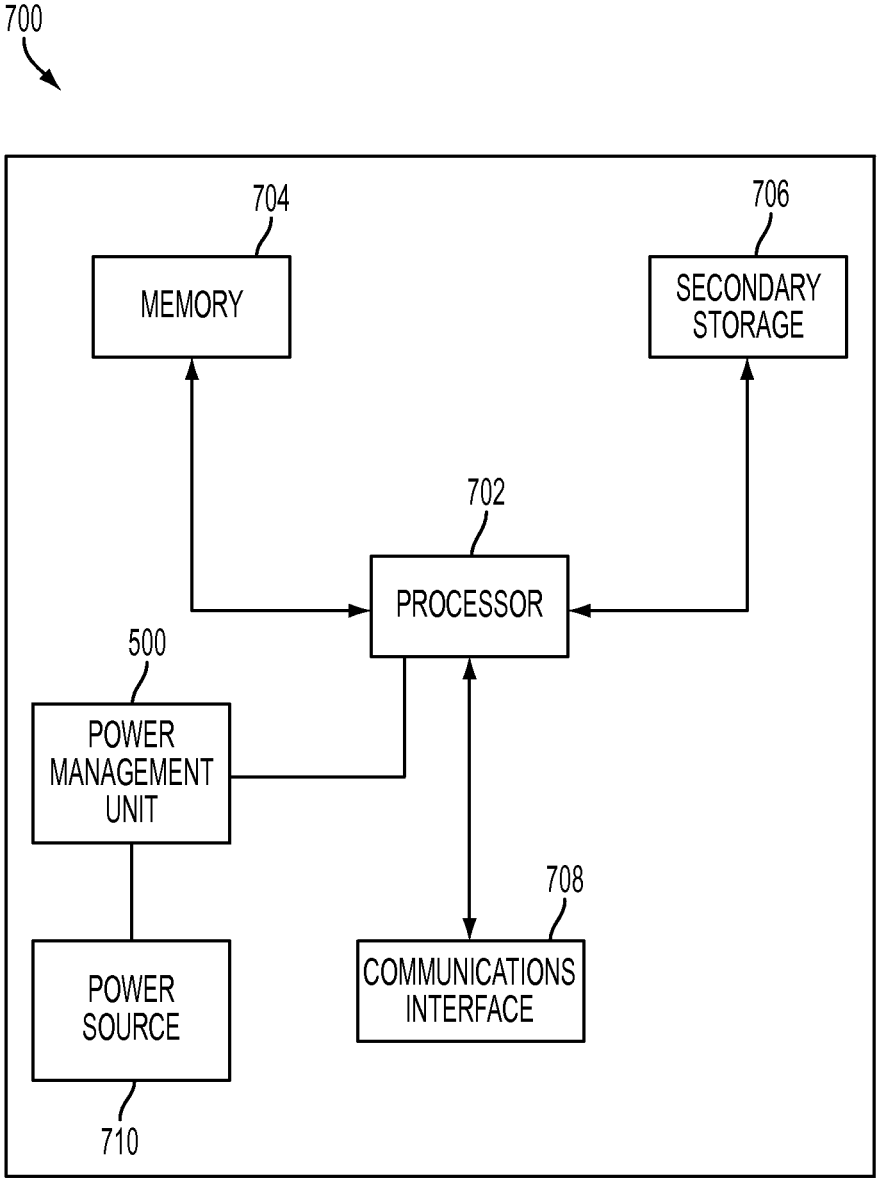
700
704
MEMORY
706
SECONDARY STORAGE
702
PROCESSOR
500
POWER MANAGEMENT UNIT
708
COMMUNICATIONS INTERFACE
POWER SOURCE
710

FIG. 7

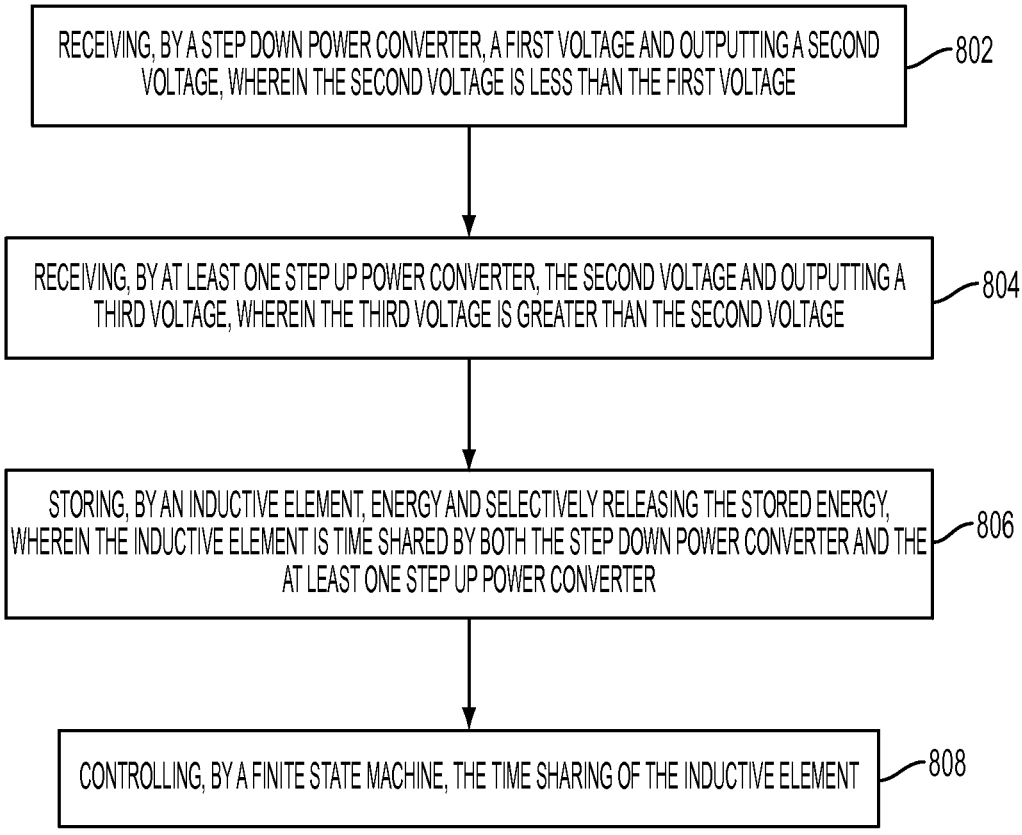
RECEIVING, BY A STEP DOWN POWER CONVERTER, A FIRST VOLTAGE AND OUTPUTTING A SECOND VOLTAGE, WHEREIN THE SECOND VOLTAGE IS LESS THAN THE FIRST VOLTAGE
802
RECEIVING, BY AT LEAST ONE STEP UP POWER CONVERTER, THE SECOND VOLTAGE AND OUTPUTTING A THIRD VOLTAGE, WHEREIN THE THIRD VOLTAGE IS GREATER THAN THE SECOND VOLTAGE
804
STORING, BY AN INDUCTIVE ELEMENT, ENERGY AND SELECTIVELY RELEASING THE STORED ENERGY, WHEREIN THE INDUCTIVE ELEMENT IS TIME SHARED BY BOTH THE STEP DOWN POWER CONVERTER AND THE AT LEAST ONE STEP UP POWER CONVERTER
806
CONTROLLING, BY A FINITE STATE MACHINE, THE TIME SHARING OF THE INDUCTIVE ELEMENT
808

FIG. 8

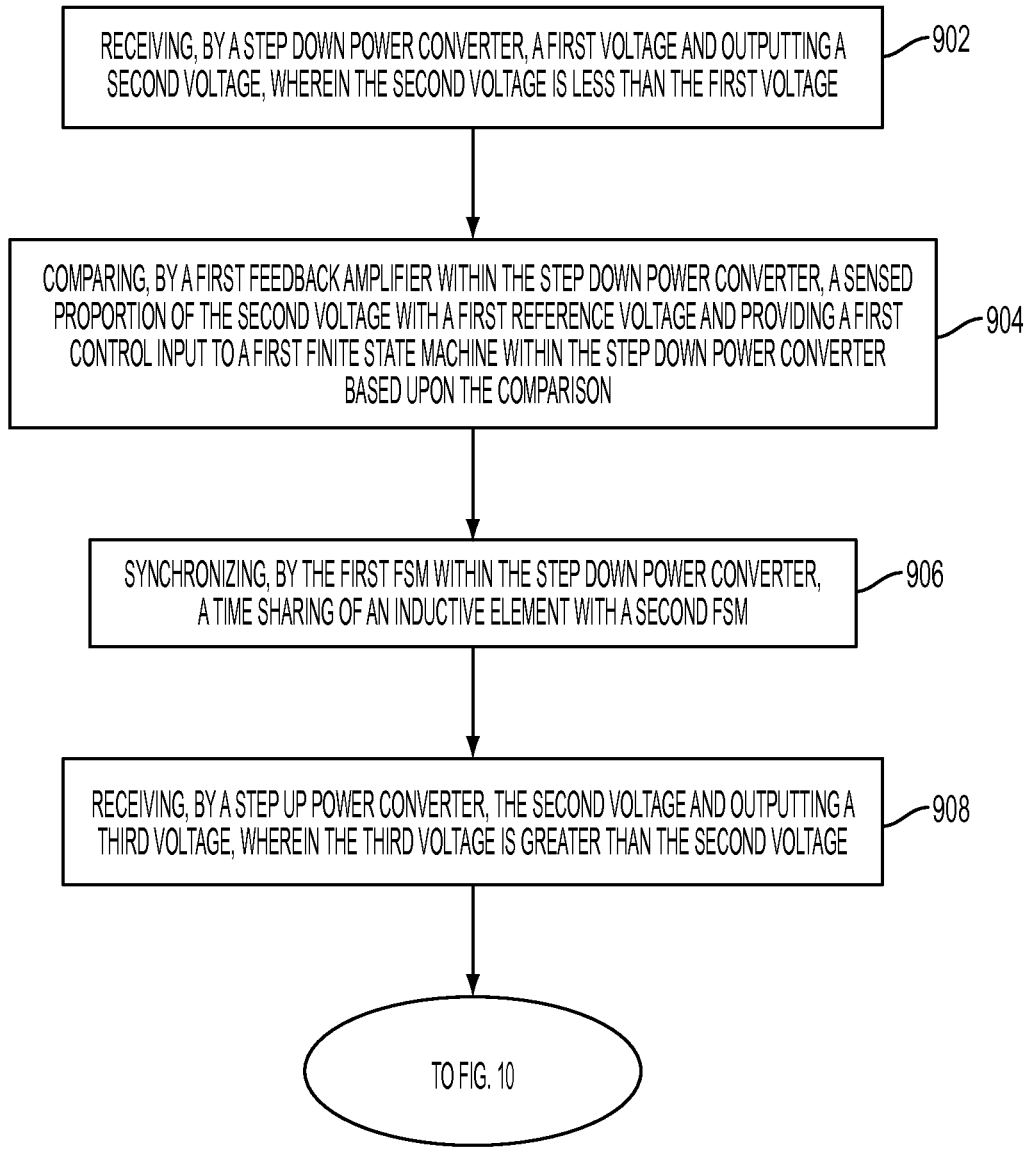
RECEIVING, BY A STEP DOWN POWER CONVERTER, A FIRST VOLTAGE AND OUTPUTTING A SECOND VOLTAGE, WHEREIN THE SECOND VOLTAGE IS LESS THAN THE FIRST VOLTAGE
902
COMPARING, BY A FIRST FEEDBACK AMPLIFIER WITHIN THE STEP DOWN POWER CONVERTER, A SENSED PROPORTION OF THE SECOND VOLTAGE WITH A FIRST REFERENCE VOLTAGE AND PROVIDING A FIRST CONTROL INPUT TO A FIRST FINITE STATE MACHINE WITHIN THE STEP DOWN POWER CONVERTER BASED UPON THE COMPARISON
904
SYNCHRONIZING, BY THE FIRST FSM WITHIN THE STEP DOWN POWER CONVERTER, A TIME SHARING OF AN INDUCTIVE ELEMENT WITH A SECOND FSM
906
RECEIVING, BY A STEP UP POWER CONVERTER, THE SECOND VOLTAGE AND OUTPUTTING A THIRD VOLTAGE, WHEREIN THE THIRD VOLTAGE IS GREATER THAN THE SECOND VOLTAGE
908
TO FIG. 10

FIG. 9

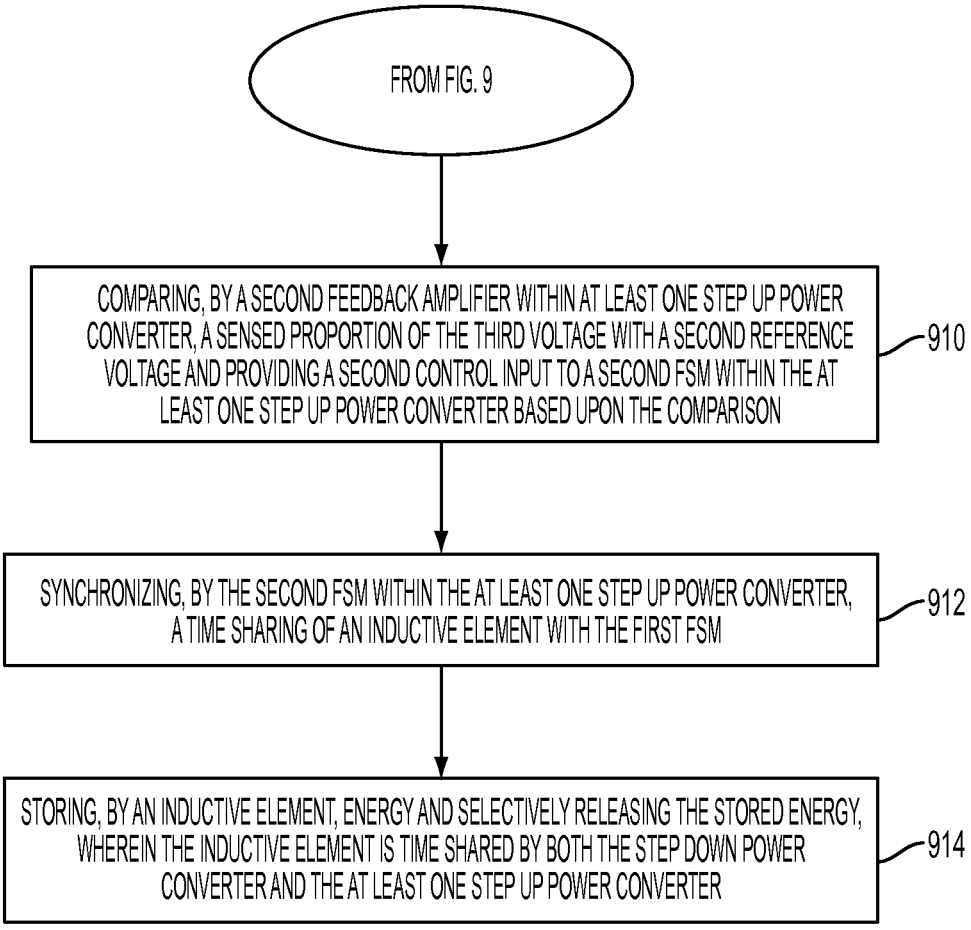
FROM FIG. 9
COMPARING, BY A SECOND FEEDBACK AMPLIFIER WITHIN AT LEAST ONE STEP UP POWER CONVERTER, A SENSED PROPORTION OF THE THIRD VOLTAGE WITH A SECOND REFERENCE VOLTAGE AND PROVIDING A SECOND CONTROL INPUT TO A SECOND FSM WITHIN THE AT LEAST ONE STEP UP POWER CONVERTER BASED UPON THE COMPARISON
910
SYNCHRONIZING, BY THE SECOND FSM WITHIN THE AT LEAST ONE STEP UP POWER CONVERTER, A TIME SHARING OF AN INDUCTIVE ELEMENT WITH THE FIRST FSM
912
STORING, BY AN INDUCTIVE ELEMENT, ENERGY AND SELECTIVELY RELEASING THE STORED ENERGY, WHEREIN THE INDUCTIVE ELEMENT IS TIME SHARED BY BOTH THE STEP DOWN POWER CONVERTER AND THE AT LEAST ONE STEP UP POWER CONVERTER
914

FIG. 10

# POWER MANAGEMENT UNIT SYSTEMS AND METHODS

## RELATED APPLICATION

This non-provisional patent application is related to, and claims priority based upon, U.S. Provisional Patent Application Ser. No. 61/416,810, filed on Nov. 4, 2010, entitled "Power Management Unit", and Indian Provisional Patent Application Serial No. IN 2909/CHE/2010 filed on Sep. 30, 2010 entitled "Power Management Unit", the disclosures of which are expressly incorporated here by reference.

## TECHNICAL FIELD

The embodiments of the subject matter disclosed herein generally relate to power management units.

## BACKGROUND

Ongoing technological developments have led to an increasing number of portable, battery-operated electronic products which in turn is generating a growing demand for energy efficient, low-power power supplies. Such products are either intrinsically low-powered or incorporate so-called "idle" or "sleep" modes of operation during which power consumption is reduced significantly compared to the power consumption of such products during their normal operating mode. Many such products generate multiple regulated direct current (DC) voltages derived from one common internal or external power source, such as a battery or a power adaptor, to comply with the power requirements of the products' internal subsystems. For example, a power supply voltage could have a voltage of 12 volts, however, an internal subsystem, e.g., a processor, might need only 2 volts. Two conventionally used devices for obtaining a desired voltage for an internal subsystem from a power supply are a step-down DC-DC power converter which is also known as a buck convertor, or a step-up DC-DC power converter which is also known as a boost converter.

The conventional buck converter **100** will now be described with respect to FIG. **1**. The buck converter **100** includes a feedback amplifier **102**, a finite state machine (FSM) **104**, switch $S_p$ **106**, switch $S_n$ **108**, inductor **114** and a capacitor **116**. Feedback amplifier **102** compares a sensed proportion of the output voltage, shown as Output Sense **110**, with a reference voltage $V_{ref}$ **112** and provides a control input to the FSM **104** based upon the comparison. Based on the received control input, the FSM **104** drives switches $S_p$ **106** and $S_n$ **108**. When switch $S_p$ **106** is closed and switch $S_n$ **108** is open, the input voltage $V_{dd}$ **120** goes through the inductor **114** substantially without ohmic loss and charges capacitor **116**. When switch $S_p$ **106** is open and switch $S_n$ **108** is closed, the buck converter **100** maintains a circulating charge to Ground **118**. A typical example of an output voltage obtained from a conventional buck converter **100** can be $V_{out}$=1.2 Volts when the source voltage $V_{dd}$=5.5 Volts.

The conventional boost converter **200** will now be described with respect to FIG. **2**. The boost converter **200** includes a feedback amplifier **202**, a FSM **204**, switch $S_p$ **206**, switch $S_n$ **208**, an inductor **210** and a capacitor **212**. The feedback amplifier **202** compares a sensed proportion of the output voltage, shown as Output Sense **214**, with a reference voltage $V_{ref}$ **216** and provides a control input to the FSM **204** based upon the comparison. Based on the received control input, the FSM **204** drives switches $S_p$ **206** and $S_n$ **208**. When switch $S_n$ **208** is closed and switch $S_p$ **206** is open, the current flows from the input voltage $V_{dd}$ **218** through inductor **210** to ground **220**. The amount of the current and the correspondingly stored energy in the inductor **210** increases over the time for which $S_n$ **208** remains closed. When switch $S_n$ **208** is open and switch $S_p$ **206** is closed, the energy stored in the inductor **210** can be transferred to the capacitor **212** and/or a load at the output **222** of the boost converter **200**. A typical example of an output voltage obtained from a conventional boost converter **200** can be $V_{out}$=6.5 Volts when the source voltage $V_{dd}$ **218** is 3.6 Volts.



In conventional designs of buck converters **100** and boost converters **200**, as described above, each converter uses its own dedicated inductor **114**, **210**. Each inductor **114**, **210** is relatively expensive and also occupies scarce circuit board real-estate. For applications which require multiple, regulated DC voltages derives from a common internal or external power source, such as a battery or a power adaptor, these cost and space issues can become aggravated.

Accordingly, systems and methods for improving the use of power converters which use inductors are desirable.

## SUMMARY

Exemplary embodiments describe using a power management unit in, for example, cellular communication devices, cellular communication subsystems, battery powered tracking devices, and the like. By using the exemplary power management unit systems and methods described herein, an object of providing more efficient power management can be obtained.

According to an exemplary embodiment there is a power management unit including: a step-down power converter configured to receive a first voltage and output a second voltage, wherein the second voltage is less than the first voltage and at least one step-up power converter configured to receive the second voltage and output a third voltage, wherein the third voltage is greater than the second voltage. The power management unit also includes an inductive element connected to the step-down power converter and the at least one step-up power converter and configured to store energy and selectively release the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter; and a finite state machine (FSM) configured to control the time sharing of the inductive element.

The step-down power converter may include a first switch which, when closed, outputs the second voltage to the at least one step-up power converter when a second switch is open. The FSM may be further configured to send control signals to open and close the first and second switches. The at least one step-up power converter may include a third switch which, when closed, outputs the third voltage from the at least one step-up power converter when a fourth switch is open. The FSM may be further configured to send control signals to open and close the third and fourth switches. The power management may also include a capacitor connected to the inductive element and configured to receive and store an electrical charge. At least one of the power converters may operate in a discontinuous mode. Additionally, the step-down power converter and each of the at least one step-up power converters may include an FSM.

According to another exemplary embodiment there is a power management unit including: a step-down power converter configured to receive a first voltage and output a second voltage, wherein the second voltage is less than the first voltage, the step-down power converter including: a first feedback amplifier configured to compare a sensed propor-

tion of the second voltage with a first reference voltage and configured to provide a first control input to a first finite state machine (FSM) based upon the comparison; and the first FSM configured to synchronize a time sharing of an inductive element with a second FSM. The power management unit also includes at least one step-up power converter configured to receive the second voltage and output a third voltage, wherein the third voltage is greater than the second voltage, the at least one step-up power converter including: a second feedback amplifier configured to compare a sensed proportion of the third voltage with a second reference voltage and configured to provide a second control input to the second FSM upon the comparison; and the second FSM configured to synchronize the time sharing of the inductive element with the first FSM. Additionally, the power management unit includes an inductive element connected to the step-down power converter and the at least one step-up power converter and configured to store energy and selectively release the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter.

The power management unit may include a linear regulator connected to the at least one step-up power converter and configured to generate an output voltage. The step-down power converter may include a first switch which, when closed, outputs the second voltage to the at least one step-up power converter when a second switch is open. The first FSM may be further configured to send control signals to open and close the first and second switches. The step-up power converter may include a third switch which, when closed, outputs the third voltage from the at least one step-up power converter when a fourth switch is open. The second FSM may be further configured to send control signals to open and close the third and fourth switches. The power management also may include a capacitor connected to the inductive element and configured to receive and store an electrical charge. Additionally, at least one of the power converters may operate in a discontinuous mode.

According to another exemplary embodiment there is a method for operating a power management unit. The method includes: receiving, by a step-down power converter, a first voltage and outputting a second voltage, wherein the second voltage is less than the first voltage; receiving, by at least one step-up power converter, the second voltage and outputting a third voltage, wherein the third voltage is greater than the second voltage. The method also includes storing, by an inductive element, energy and selectively releasing the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter; and controlling, by a finite state machine (FSM), the time sharing of the inductive element.

The method for operating a power management unit also may include closing a first switch and opening a second switch in the step-down power converter which outputs the second voltage to the at least one step-up power converter and sending control signals, by the FSM, to open and close the first and second switches. The method also may include closing a third switch and opening a fourth switch in the at least one step-up power converter which outputs the third voltage from the at least one step-up power converter and sending control signals, by the FSM, to open and close the third and fourth switches. Additionally, the method may include receiving and storing an electrical charge by a capacitor, operating at least one of the power converters in a discontinuous mode and wherein the step-down power converter and each of the at least one step-up power converters includes an FSM.

According to another exemplary embodiment there is another method for operating a power management unit. The method includes: receiving, by a step-down power converter, a first voltage and outputting a second voltage, wherein the second voltage is less than the first voltage; comparing, by a first feedback amplifier within the step-down power converter, a sensed proportion of the second voltage with a first reference voltage and providing a first control input to a first finite state machine (FSM) within the step-down power converter based upon the comparison; synchronizing, by the first FSM within the step-down power converter, a time sharing of an inductive element with a second FSM; and receiving, by a step-up power converter, the second voltage and outputting a third voltage, wherein the third voltage is greater than the second voltage. The method also includes comparing, by a second feedback amplifier within at least one step-up power converter, a sensed proportion of the third voltage with a second reference voltage and providing a second control input to a second FSM within the at least one step-up power converter based upon the comparison; synchronizing, by the second FSM within the at least one step-up power converter, a time sharing of an inductive element with the first FSM; and storing, by an inductive element, energy and selectively releasing the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter.

The method for operating a power management unit also may include generating, by a linear regulator, an output voltage, closing a first switch and opening a second switch in the step-down power converter which outputs the second voltage to the at least one step-up power converter and sending control signals, by the FSM, to open and close the first and second switches. Additionally, the method also may include closing a third switch and opening a fourth switch in the at least one step-up power converter which allows the third voltage to exit the at least one step-up power converter and sending control signals, by the FSM, to open and close the third and fourth switches. Also the method may include receiving and storing an electrical charge by a capacitor and operating at least one of the power converters in a discontinuous mode.

## BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings illustrate exemplary embodiments, wherein:

FIG. **1** illustrates a schematic representation of a conventional buck converter;

FIG. **2** shows a schematic representation of a conventional boost converter;

FIG. **3** illustrates a block diagram representation of a power management unit according to exemplary embodiments;

FIG. **4**(*a*) shows a schematic representation of a power management unit according to exemplary embodiments;

FIG. **4**(*b*) shows the power management unit of FIG. **4**(*b*) including a plurality of feedback amplifiers according to exemplary embodiments;

FIG. **5**(*a*) illustrates a schematic representation of another power management unit according to exemplary embodiments;

FIG. **5**(*b*) shows the power management unit of FIG. **5**(*a*) including a plurality of boost converters and linear regulators according to exemplary embodiments;

FIG. **6** shows simulation results according to an exemplary embodiment;

FIG. **7** illustrates a device according to exemplary embodiments;

FIG. **8** is a flowchart illustrating a method according to exemplary embodiments; and

FIGS. **9-10** are a flowchart illustrating another method according to exemplary embodiments.

## DETAILED DESCRIPTION

The following detailed description of the exemplary embodiments refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. Additionally, the drawings are not necessarily drawn to scale. Also, the following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims.

Reference throughout the specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with an embodiment is included in at least one embodiment of the subject matter disclosed. Thus, the appearance of the phrases "in one embodiment" or "in an embodiment" in various places throughout the specification is not necessarily referring to the same embodiment. Further, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

According to exemplary embodiments described below, it is possible to improve the efficiency of power management units and methods for their use in various devices, e.g., cellular communication devices, cellular communication subsystems, battery powered tracking devices, and the like. The various exemplary embodiments described herein illustrate different systems and methods which can be used alone or in combination depending upon the desired application for improving the efficiency of power management units.

According to an exemplary embodiment, a block diagram representation of an exemplary power management unit **300** is shown in FIG. **3**. The power management unit **300** includes a step-down power converter, e.g., a buck converter **302**, which can be configured to receive a supply voltage $V_{in}$ **304** and one or more step-up power converters, e.g., boost converters **306(1)**, **306(2)** . . . **306(*n*)**, which have their respective inputs coupled to a switching output of the buck converter **302**. A single inductive element **308**, e.g., an inductor, can be included which can be shared for use by all of the converters **302**, **306(1)**, **306(2)** . . . **306(*n*)** in a time multiplexed arrangement. Additionally, the inductive element **308** is coupled to a switching output $V_{sw}$ **320** and a capacitor **322**. The power management unit **300** also includes a finite state machine (FSM) **310** which can be configured to provide control signals to enable the time multiplexed sharing of the common inductive element **308** between the various converters **302**, **306(1)**, **306(2)** . . . **306(*n*)**. This time multiplexed sharing of the common inductive element **308** is described in more detail below.

According to an exemplary embodiment, the buck converter **302** is configured to output voltage $OUT_{buck}$ **312**, which has a lower voltage than the received supply voltage $V_{in}$ **304**. The boost converters **302(1)**, **302(2)** . . . **302(*n*)** can be configured to output voltages $OUT_{boost1}$ **314**, $OUT_{boost2}$ **316** . . . $OUT_{boostn}$ **318**, associated with the boost converters **302(1)**, **302(2)** . . . **302(*n*)** respectively, which output voltages are greater than the voltage $OUT_{buck}$ **312**. According to an alternative exemplary embodiment, each converter **302**, **306(1)**, **306(2)** . . . **306(*n*)** can have a dedicated FSM **310** which may be synchronized to provide the time multiplexed control of the common inductive element **308**. According to another alternative exemplary embodiment, one or more FSMs **310** can be shared between two or more power converters.

According to another exemplary embodiment, the operation of another power management unit **400** is now described with respect to FIG. **4**. The power management unit **400** includes a buck converter **402** and one or more boost converters **416(1)**, **416(2)** . . . **416(*n*)**. The buck converter **402** includes switch $S_{p,buck}$ **404** and switch $S_{n,buck}$ **406**, and can provide an output $OUT_{buck}$ **408** through a common inductive element **410**, e.g., an inductor, which can store and release energy. The common inductive element **410** is connected to a switching node $V_{sw}$ **433** and a capacitor. According to an exemplary embodiment, when operating in relatively low power modes of operation, the switching converters in the power management unit **400** can operate in a discontinuous mode, i.e., the inductive element **410** will be completely discharged at the end of the commutation cycle. When switch $S_{p,buck}$ **404** is closed, and all other switches shown in FIG. **4** are open, current flows into an output $OUT_{buck}$ **408** from the input voltage $V_{in}$ **412** through the inductive element **410**. When the current in the inductive element **410** exceeds a predetermined limit, e.g., 200 mA-400 mA, the FSM **414** opens the switch $S_{p,buck}$ **404** and closes the switch $S_{n,buck}$ **406**. Upon opening the switch $S_{p,buck}$ **404** and closing the switch $S_{n,buck}$ **406** the current, previously stored in the inductive element **410**, leaves the inductive element **410** with a rate which can be described as having a constant slope. When the inductive current becomes substantially zero, the FSM **414** opens the switch $S_{n,buck}$ **406** and makes the inductive element **410** available for use by the boost converters **416(1)**, **416(2)** . . . **416(*n*)**.

According to exemplary embodiments, the inductive element **410** may be used in a sequential manner by the boost converters **416(1)**, **416(2)** . . . **416(*n*)**. The FSM **414** can then close switch $S_{p,boost1}$ **418** of boost converter **416(1)** while all of the remaining switches in the power management unit **400** remain open. The FSM **414** can then open switch $S_{p,boost1}$ **418** and close switch $S_{n,boost1}$ **420** of boost converter **416(1)** while all of the remaining switches remain open in the power management unit **400**. The FSM **405** can then close $S_{n,boost1}$ **420**, thus making the inductive element **410** available for use in turn for the remaining boost converters **416(2)** . . . **416(*n*)**. Subsequently, the FSM **414** can close switch $S_{p,boost2}$ **422** of boost converter **416(2)** while all of the remaining switches in the power management unit **400** remain open. The FSM **414** can then open $S_{p,boost2}$ **422** and turn on $S_{n,boost2}$ **424** of the boost converter **416(2)** while all of the remaining switches are still open. The FSM **414** can continue this pattern of switch management in the rest of the boost converters as desired, which allows for the time multiplexed sharing of the inductive element **410**. This in turn can provide regulated output voltages for $OUT_{boost1}$ **426**, $OUT_{boost2}$ **428** . . . $OUT_{boostn}$ **430**.

According to an alternative exemplary embodiment, other forms of time sharing of the inductive element **410** can be used. For example, instead of providing the inductive element **410** to the converters sequentially, the inductive element **410** can be provided to the converters on an as needed basis, preferably with the buck converter **402** having the highest priority. This can be done by having the feedback amplifiers associated with each converter transmit a signal to the FSM **414** indicating the converter's desire to use the inductive element **410**. For example, referring to FIG. **4**(*b*), the buck converter feedback amplifier **434** receives as an input **436** the output voltage of the buck converter **402**. When the output voltage falls below its reference voltage, a signal **438** is transmitted to the FSM **414** which indicates that the buck converter **402** desires to use the inductive element **410**. The boost converters **416(1)** and **416(2)** have their respective feedback amplifiers **440** and **442** which can operate in a similar manner.

The FSM **414** receives these signals and can then provide control signals to the various switches in the converters **402**, **416**(**1**) and **416**(**2**) to allocate the inductive element **410** as desired.

According to another exemplary embodiment, FIG. **5** illustrates a schematic representation of another power management unit **500** which can facilitate operation during relatively low power consumption, e.g., sleep mode of operation of a system such as a cellular phone, and can also facilitate operation during relatively high power consumption, e.g., operating in an active mode of a system such as a cellular phone. The power management system **500** can include a buck converter **502**, a boost converter **504**, a commonly shared inductive element **506** and a capacitor **508** which is connected in series to the inductive element **506**. The power management **500** unit can also include a linear regulator **510** which may, for example, operate during the active mode of operation of the system.

The buck converter **502** can include a feedback amplifier **512**, an FSM **514**, a switch $S_{p,buck}$ **516** and a switch $S_{n,buck}$ **518**. The buck converter **502** receives a supply voltage $V_{dd}$ **520** which is also used by the feedback amplifier **512** within the buck converter **502**. When switch $S_{p,buck}$ **516** is closed, current flows to an output through the inductor **506** to provide an output voltage $OUT_{buck}$ **522** of the buck converter **502**. The output voltage $OUT_{buck}$ **522** can be fed back to one input (the negative input) of the feedback amplifier **512**, while a reference voltage $V_{ref}$ **524** is supplied to another input (the positive input) of the feedback amplifier **512**. Feedback amplifier **512** compares a sensed proportion of the output voltage with a reference voltage $V_{ref}$ **524** and provides a control input to the FSM **102** based upon the comparison. A switching output $V_{sw}$ **526** can be provided for use as an input voltage to the boost converter **504**.

According to exemplary embodiments, the boost converter **504** can include a feedback amplifier **530**, an FSM **532**, a switch $S_{p,boost}$ **534** and a switch $S_{p,boost}$ **536**. Upon receiving $V_{sw}$ **526** as the input voltage to the boost converter **504**, the boost converter **504** can provide an output $OUT_{boost}$ **538** when switch $S_{p,boost}$ **534** is closed. This output voltage $OUT_{boost}$ shown as point **538** can then be delivered to the linear regulator **510**. The linear regulator **510** can be configured to facilitate operation of the power management unit **500** under relatively high current load requirements by generating an output voltage as desired. For example, in some exemplary embodiments, a load profile of the buck converter **502** may not be predictable. Therefore, the boost converter **504** may not be guaranteed availability of the common inductive element **506** at all times that the boost converter **504** may desire use of the common inductive element **506**. This can occur when the buck converter **502** is using the common inductive element **506** which in turn prevents the function of the boost converter **504**. Therefore, in some exemplary embodiments, the linear regulator **510** may be functional at all (or many) times.

Regarding the linear regulator **510**, the linear regulator **510** includes a feedback amplifier **548**, and a p-type metal oxide semiconductor field effect transistor **546** to drive current from the input supply $V_{in}$ **552** to an output. As the boost converter **504** is in operation, the boost converter's output voltage $OUT_{boost}$ shown as point **538** is slightly higher than the reference voltage $V_{ref}$ **550** of the linear regulator **510**. This creates the situation where the feedback amplifier's output is high enough to turn off the p-type metal oxide semiconductor field effect transistor **546** and hence the linear regulator **510** as well. When the boost converter **504** is turned off in, for example, relatively high power conditions, the output voltage drops as neither the boost convertor **504** nor the linear regulator **510** are driving the output voltage high enough. When the output voltage drops below a scaled proportion of the linear regulator's $V_{ref}$ **550** the linear regulator, which may be a low-dropout linear regulator, turns on substantially immediately.

According to another exemplary embodiment, the power management unit **500** shown in FIG. **5**(*a*) can be expanded to include a plurality of boost converters **504**(**1**), **504**(**2**) and linear regulators **510**(**1**), **510**(**2**) as shown in FIG. **5**(*b*). Time sharing of the inductive element **506** can be done by having the feedback amplifiers **540**, **542**, **544** associated with each converter transmit a signal to the FSM **538** indicating the converter's desire to use the inductive element **506**. While shown in FIG. **5**(*b*) as there being a single FSM **538**, each converter **502**, **504**(**1**) and **504**(**2**) can have its own FSM **538** (similar to what is shown in FIG. **5**(*a*)). The FSM **538** (or FSMs which can communicate with each other) can provide control signals to the various switches in the converters **502**, **504**(**1**) and **504**(**2**) to allocate the inductive element **506** as desired.

According to another exemplary embodiment, the buck converters **302**, **402** and **502** can be given the highest priority for access to their respective common inductive elements **308**, **410** and **506**. In support of this prioritization, the FSM or FSMs **310**, **414**, **514** and **532** can be configured such that when the buck converters **302**, **402** and **502** require the use of their respective inductive element **308**, **410** and **506**, for use according to the exemplary embodiments associated with FIGS. **3**-**5**, the other boost converters **306**, **416** and **504** are prevented from accessing their respective common inductive element **308**, **410** and **506**.

According to an exemplary embodiment, FIG. **6** shows a simulation output for the power management unit **500** shown in FIG. **5**. The simulation output **600** can be broken down into three sections as follows: (1) a top section **602** which shows the inductor current over time, (2) a middle section **604** which shows the buck output voltage, e.g., $V_{sw}$ **526**, over time and (3) the bottom section which shows the boost converter output voltage, e.g., $OUT_{boost}$ shown as point **538**. Positive spikes **608** in the inductor current correspond to times when the buck converter **502** is using the common inductive element **506**. This usage by the buck converter **502** of the common inductive element **506** is also reflected in the middle section **604** by positive steps **610** in the buck output voltage curve **612**. Negative spikes **614** in the inductor current correspond to times when the boost converter **504** is using the common inductive element **506**. This usage by the boost converter **504** is also reflected in the bottom section **606** by the positive steps **616** in the boost output voltage curve **618**.

According to exemplary embodiments, the relatively low power modes of operation which the exemplary embodiments described herein support, e.g., cellular communication devices, cellular communication subsystems, battery powered tracking devices, and the like, can cause the switching converter(s) to operate in a discontinuous mode. Periodically, for very short intervals of time, e.g., 100 ns in a 10 μs time frame, the inductive element **506** can deliver an electrical charge to the capacitor **508** that supplies the load current, therefore the inductive element **506** does not always need to carry current for long periods of time rendering the inductive element **506** available for use.

According to an exemplary embodiment, a purely illustrative example of efficiency, for the embodiments described with respect to FIGS. **5** and **6**, is now described. For this example, a supply voltage is 3.6V, the linear regulator **510** output is 1.8V, a linear regulator **510** load current is 600 μA,

a linear regulator quiescent current is 20 μA and a current drawn from a supply is 620 μA. Additionally, the assumptions shown below in Table 1 are used.

TABLE 1

| | |
|---|---|
| Buck Converter Output Voltage | 1.2 V |
| Buck Converter Efficiency | 85% |
| Boost Converter Efficiency | 85% |

If all of the 600 μA load current is supplied by the boost converter(s) **504**, the current drawn from the supply can be computed as shown in Equation (1) below.

$$600\ \mu A \times \frac{1.8}{1.2} \times \frac{1}{0.8} \times \frac{1.2}{3.6} \times \frac{1}{0.8} = 468\ \mu A \quad (1)$$

According to this purely illustrative example, this can provides for a savings of 152 μA, which in a cellular subsystem can reduce the overall Discontinuous Reception 2 (DRX2) sleep mode power consumption by almost fifteen percent.

According to exemplary embodiments, an inductive element **506** can be used by multiple functional elements within a power management unit **500**. According to an exemplary embodiment, on average a cellular subsystem operates on low power, also referred to as "sleep mode", for approximately 23 hours a day. Therefore, the step-down power converter, e.g., the buck converter **502**, can run in sleep mode to ensure lower power consumption and higher efficiency using the exemplary embodiments described herein which allow for the inductive element **506** to be used in operating one or more step-up power converters, e.g., the boost converters **504**.

The exemplary embodiments described above can allow a single inductive element to support multiple power converters within a power management system. An exemplary device **700**, can be a, e.g., cellular communication devices, cellular communication subsystems, battery powered tracking devices, and the like, will now be described with respect to FIG. **7**. The device **700** can include a processor **702** (or multiple processor cores), memory **704**, one or more secondary storage devices **706**, a communications interface, a power management unit **710** and a power source **712**. The power management unit **710** can be any of, but is not limited to, the power management units **300**, **400** and **500** as desired for device **700** to reduce the overall power consumption of the device **700**.

An exemplary method for operating a power management unit is illustrated in FIG. **8**. Therein, at step **802** receiving, by a step-down power converter, a first voltage and outputting a second voltage, wherein the second voltage is less than the first voltage; at step **804** receiving, by at least one step-up power converter, the second voltage and outputting a third voltage, wherein the third voltage is greater than the second voltage; at step **806** storing, by an inductive element, energy and selectively releasing the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter; and at step **808** controlling, by a finite state machine, the time sharing of the inductive element.

Another exemplary method for operating a power management unit is illustrated in FIGS. **9** and **10**. Therein, at step **902** receiving, by a step-down power converter, a first voltage and outputting a second voltage, wherein the second voltage is less than the first voltage; at step **904** comparing, by a first feedback amplifier within the step-down power converter, a sensed proportion of the second voltage with a first reference voltage and providing a first control input to a first finite state machine within the step-down power converter based upon the comparison; at step **906** synchronizing, by the first FSM within the step-down power converter, a time sharing of an inductive element with a second FSM; at step **908** receiving, by a step-up power converter, the second voltage and outputting a third voltage, wherein the third voltage is greater than the second voltage; at step **910** comparing, by a second feedback amplifier within at least one step-up power converter, a sensed proportion of the third voltage with a second reference voltage and providing a second control input to a second FSM within the at least one step-up power converter based upon the comparison; at step **912** synchronizing, by the second FSM within the at least one step-up power converter, a time sharing of an inductive element with the first FSM; at step **914** storing, by an inductive element, energy and selectively releasing the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter.

The use of the above described exemplary embodiments can allow for a power management unit which is capable of efficiently generating multiple voltage outputs from a single power source using a single inductor. Additionally, the use of the above described exemplary embodiments can allow for a power management unit which uses a relatively small area on a circuit board due to the reduction of components, e.g., reducing the quantity of inductors.

The above-described exemplary embodiments are intended to be illustrative in all respects, rather than restrictive, of the present invention. Thus the present invention is capable of many variations in detailed implementation that can be derived from the description contained herein by a person skilled in the art. All such variations and modifications are considered to be within the scope and spirit of the present invention as defined by the following claims. No element, act, or instruction used in the description of the present application should be construed as critical or essential to the invention unless explicitly described as such. Also, as used herein, the article "a" is intended to include one or more items. Skilled readers will readily acknowledge that these are provided to illustrate the teachings of the invention and should not be construed as the only possible implementations of the present invention.

This written description uses examples of the subject matter disclosed to enable any person skilled in the art to practice the same, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the subject matter is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

What is claimed is:

**1**. A power management unit comprising:

a step-down power converter configured to receive a first voltage and output a second voltage, wherein the second voltage is less than the first voltage, the step-down power converter including:

a first feedback amplifier configured to compare a sensed proportion of the second voltage with a first reference voltage and configured to provide a first control input to a first finite state machine (FSM) based upon the comparison; and

the first FSM configured to synchronize a time sharing of an inductive element with a second FSM;

at least one step-up power converter configured to receive the second voltage and output a third voltage, wherein

the third voltage is greater than the second voltage, the at least one step-up power converter including:

a second feedback amplifier configured to compare a sensed proportion of the third voltage with a second reference voltage and configured to provide a second control input to the second FSM upon the comparison; and

the second FSM configured to synchronize the time sharing of the inductive element with the first FSM; and

the inductive element connected to the step-down power converter and the at least one step-up power converter and configured to store energy and selectively release the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter.

**2**. The power management unit of claim **1**, further comprising:

a linear regulator connected to the at least one step-up power converter and configured to generate an output voltage.

**3**. The power management unit of claim **1**, wherein the step-down power converter comprises:

a first switch which, when closed, outputs the second voltage to the at least one step-up power converter when a second switch is open.

**4**. The power management unit of claim **3**, wherein the first FSM is further configured to send control signals to open and close the first and second switches.

**5**. The power management unit of claim **1**, wherein the step-up power converter comprises:

a third switch which, when closed, outputs the third voltage from the at least one step-up power converter when a fourth switch is open.

**6**. The power management unit of claim **5**, wherein the second FSM is further configured to send control signals to open and close the third and fourth switches.

**7**. The power management unit of claim **1**, further comprising:

a capacitor connected to the inductive element and configured to receive and store an electrical charge.

**8**. The power management unit of claim **1**, wherein at least one of the power converters operates in a discontinuous mode.

**9**. A method for operating a power management unit, the method comprising:

receiving, by a step-down power converter, a first voltage and outputting a second voltage, wherein the second voltage is less than the first voltage;

comparing, by a first feedback amplifier within the step-down power converter, a sensed proportion of the second voltage with a first reference voltage and providing a first control input to a first finite state machine (FSM) within the step-down power converter based upon the comparison;

synchronizing, by the first FSM within the step-down power converter, a time sharing of an inductive element with a second FSM;

receiving, by a step-up power converter, the second voltage and outputting a third voltage, wherein the third voltage is greater than the second voltage;

comparing, by a second feedback amplifier within at least one step-up power converter, a sensed proportion of the third voltage with a second reference voltage and providing a second control input to a second FSM within the at least one step-up power converter based upon the comparison;

synchronizing, by the second FSM within the at least one step-up power converter, a time sharing of the inductive element with the first FSM; and

storing, by the inductive element, energy and selectively releasing the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter.

**10**. The method of claim **9**, further comprising:

generating, by a linear regulator, an output voltage.

**11**. The method of claim **9**, further comprising:

closing a first switch and opening a second switch in the step-down power converter which outputs the second voltage to the at least one step-up power converter.

**12**. The method of claim **11**, further comprising:

sending control signals, by the FSM, to open and close the first and second switches.

**13**. The method of claim **9**, further comprising:

closing a third switch and opening a fourth switch in the at least one step-up power converter which allows the third voltage to exit the at least one step-up power converter.

**14**. The method of claim **13**, further comprising:

sending control signals, by the FSM, to open and close the third and fourth switches.

**15**. The method of claim **9**, further comprising:

receiving and storing an electrical charge by a capacitor.

**16**. The method of claim **9**, further comprising:

operating at least one of the power converters in a discontinuous mode.

**17**. A power management unit comprising:

a step-down power converter configured to receive a first voltage and output a second voltage, the step-down power converter including a first feedback amplifier configured to compare a sensed proportion of the second voltage with a first reference voltage;

at least one step-up power converter configured to receive the second voltage and output a third voltage, the at least one step-up power converter including a second feedback amplifier configured to compare a sensed proportion of the third voltage with a second reference voltage; and

an inductive element connected to the step-down power converter and the at least one step-up power converter and configured to store energy and selectively release the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter.

**18**. The power management unit of claim **17**, wherein the step-down power converter comprises:

a first switch which, when closed, outputs the second voltage to the at least one step-up power converter when a second switch is open.

**19**. The power management unit of claim **18**, wherein the step-up power converter comprises:

a third switch which, when closed, outputs the third voltage from the at least one step-up power converter when a fourth switch is open.

**20**. The power management unit of claim **17**, further comprising:

a capacitor connected to the inductive element and configured to receive and store an electrical charge.

**21**. A method for operating a power management unit, the method comprising:

receiving, by a step-down power converter, a first voltage and outputting a second voltage;

comparing, by a first feedback amplifier within the step-down power converter, a sensed proportion of the second voltage with a first reference voltage;

receiving, by a step-up power converter, the second voltage and outputting a third voltage, wherein the third voltage is greater than the second voltage;

comparing, by a second feedback amplifier within at least one step-up power converter, a sensed proportion of the third voltage with a second reference voltage; and

storing, by an inductive element, energy and selectively releasing the stored energy, wherein the inductive element is time shared by both the step-down power converter and the at least one step-up power converter.

**22**. The method of claim **21**, further comprising:

generating, by a linear regulator, an output voltage.

**23**. The method of claim **21**, further comprising:

closing a first switch and opening a second switch in the step-down power converter which outputs the second voltage to the at least one step-up power converter.

**24**. The method of claim **23** further comprising:

closing a third switch and opening a fourth switch in the at least one step-up power converter which allows the third voltage to exit the at least one step-up power converter.

**25**. The method of claim **21**, further comprising:

receiving and storing an electrical charge by a capacitor.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION



| | |
|---|---|
| PATENT NO. | : 9,172,303 B2 |
| APPLICATION NO. | : 13/048100 |
| DATED | : October 27, 2015 |
| INVENTOR(S) | : Vasadi et al. |

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title Page, Item 30 Insert -- Foreign Application Priority Data
Sep. 30, 2010 (IN) ..... 2909/CHE/2010 --

Signed and Sealed this
Twentieth Day of December, 2016

Michelle K. Lee

Michelle K. Lee
*Director of the United States Patent and Trademark Office*